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**Lu et al.**

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(54) **SUPERCAPACITOR WITH METAL  
CYANOMETALLATE ANODE AND  
CARBONACEOUS CATHODE**

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**Related U.S. Application Data**

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filed on Sep. 4, 2012, now Pat. No. 9,159,502, which  
is a continuation-in-part of application No.  
13/523,694, filed on Jun. 14, 2012, now Pat. No.  
8,956,760, which is a continuation-in-part of  
application No. 13/449,195, filed on Apr. 17, 2012,  
which is a continuation-in-part of application No.  
13/432,993, filed on Mar. 28, 2012, now Pat. No.  
9,269,953.

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**H01G 11/32** (2013.01)  
**H01G 11/30** (2013.01)  
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(52) **U.S. Cl.**  
CPC ..... **H01G 11/32** (2013.01); **H01G 11/30**  
(2013.01); **H02J 7/345** (2013.01); **Y02E 60/13**  
(2013.01)

(58) **Field of Classification Search**

CPC ..... H01G 11/32; H01G 11/30; H02J 7/345;  
Y02E 60/13; H01M 4/58; H01M 2/16;  
H01M 10/0525; H01M 4/583; H01M 4/38  
See application file for complete search history.

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*Primary Examiner* — Cynthia H Kelly

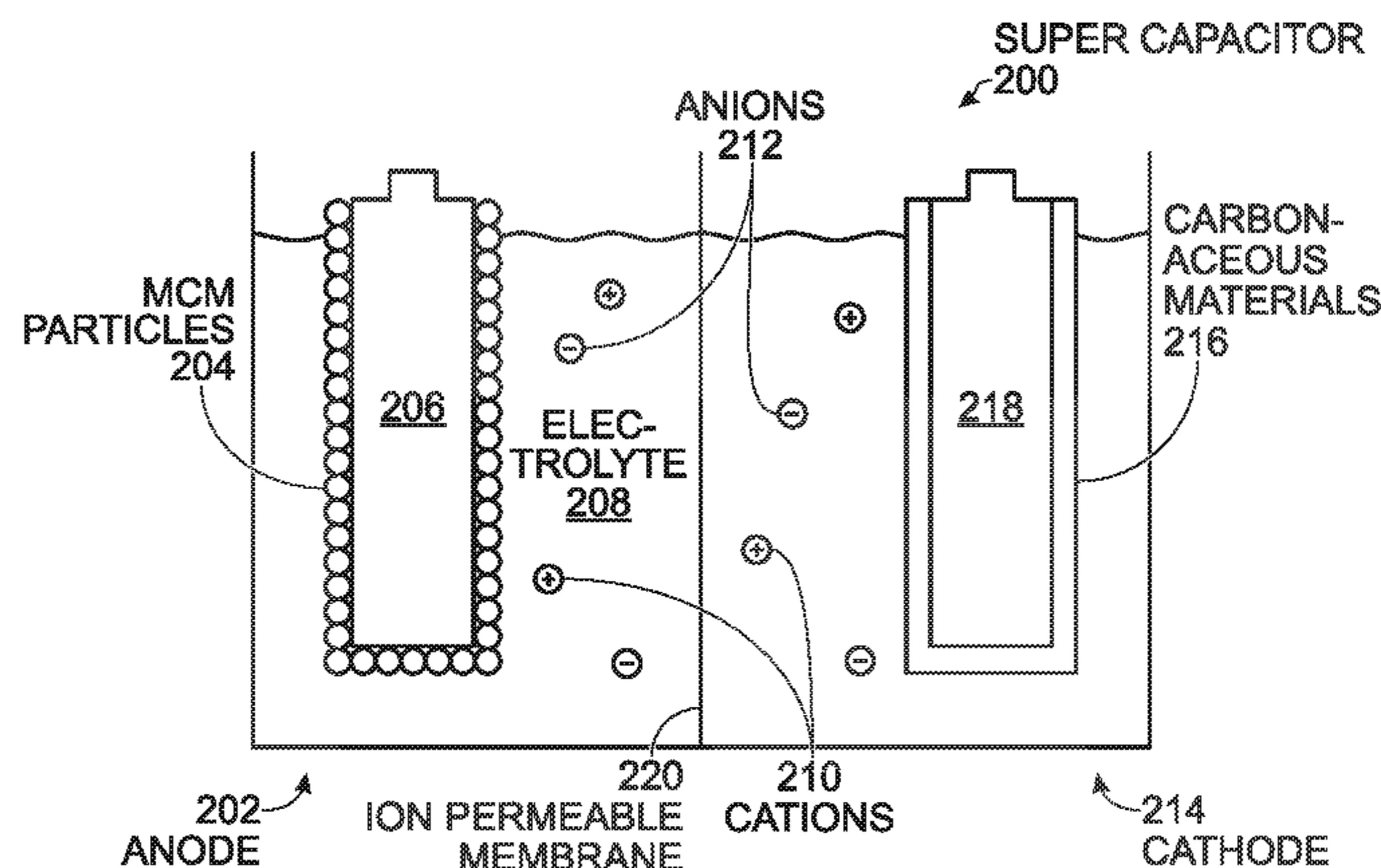
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(57) **ABSTRACT**

A method is provided for charging a supercapacitor. The  
method initially provides a supercapacitor with a metal  
cyanometallate (MCM) particle anode, an electrolyte includ-  
ing a salt (DB) made up of cations (D<sup>+</sup>) anions (B<sup>-</sup>), and a  
cathode including carbonaceous materials (□). The method  
connects an external charging device between the anode and  
cathode, and the charging device supplies electrons to the  
anode and accepting electrons from the cathode. In response  
to the charging device, cations are inserted into the anode  
while anions are absorbed on the surface of the cathode. A  
supercapacitor device is also presented.

**17 Claims, 3 Drawing Sheets**



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Fig. 1  
(PRIOR ART)

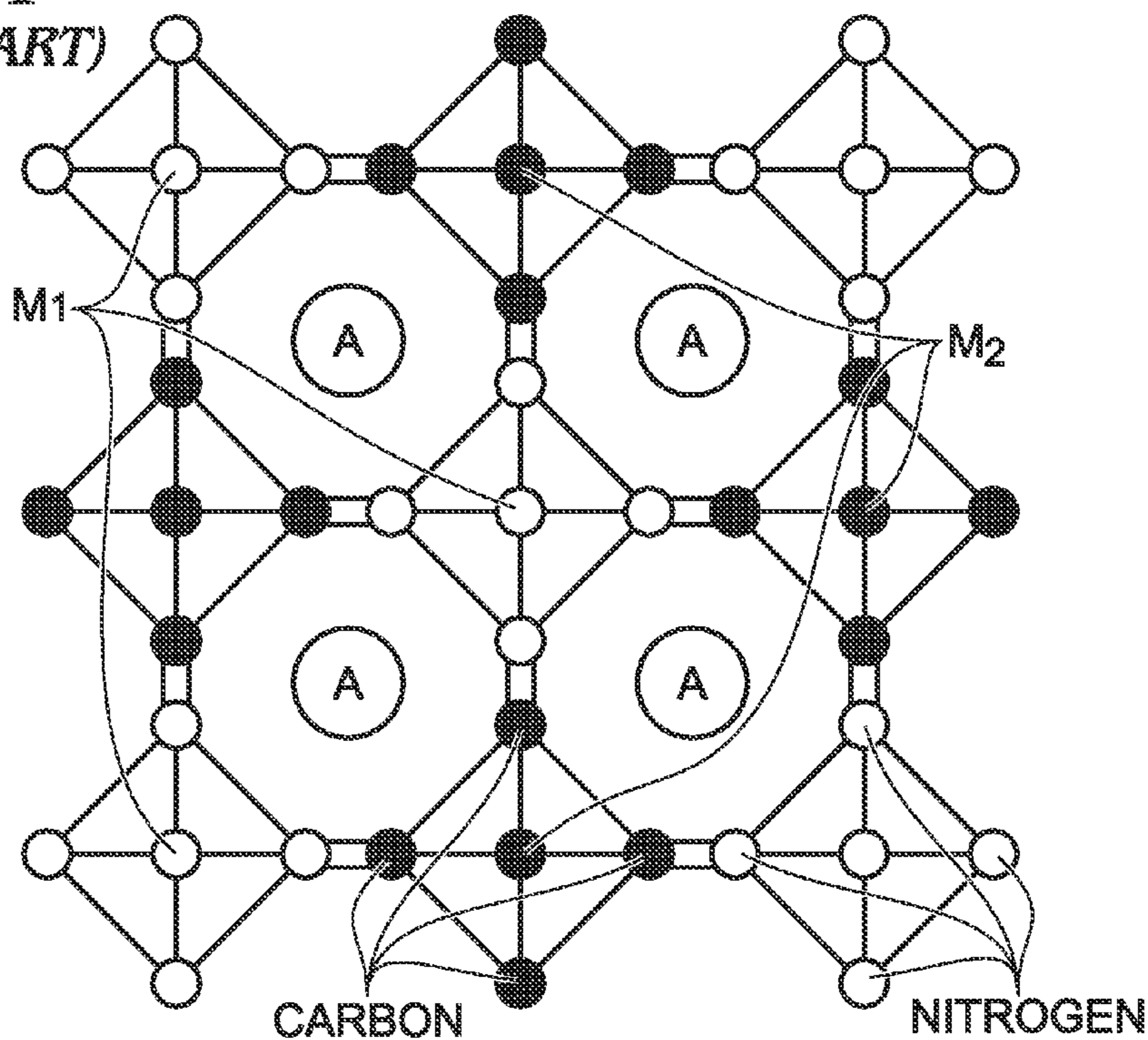


Fig. 2

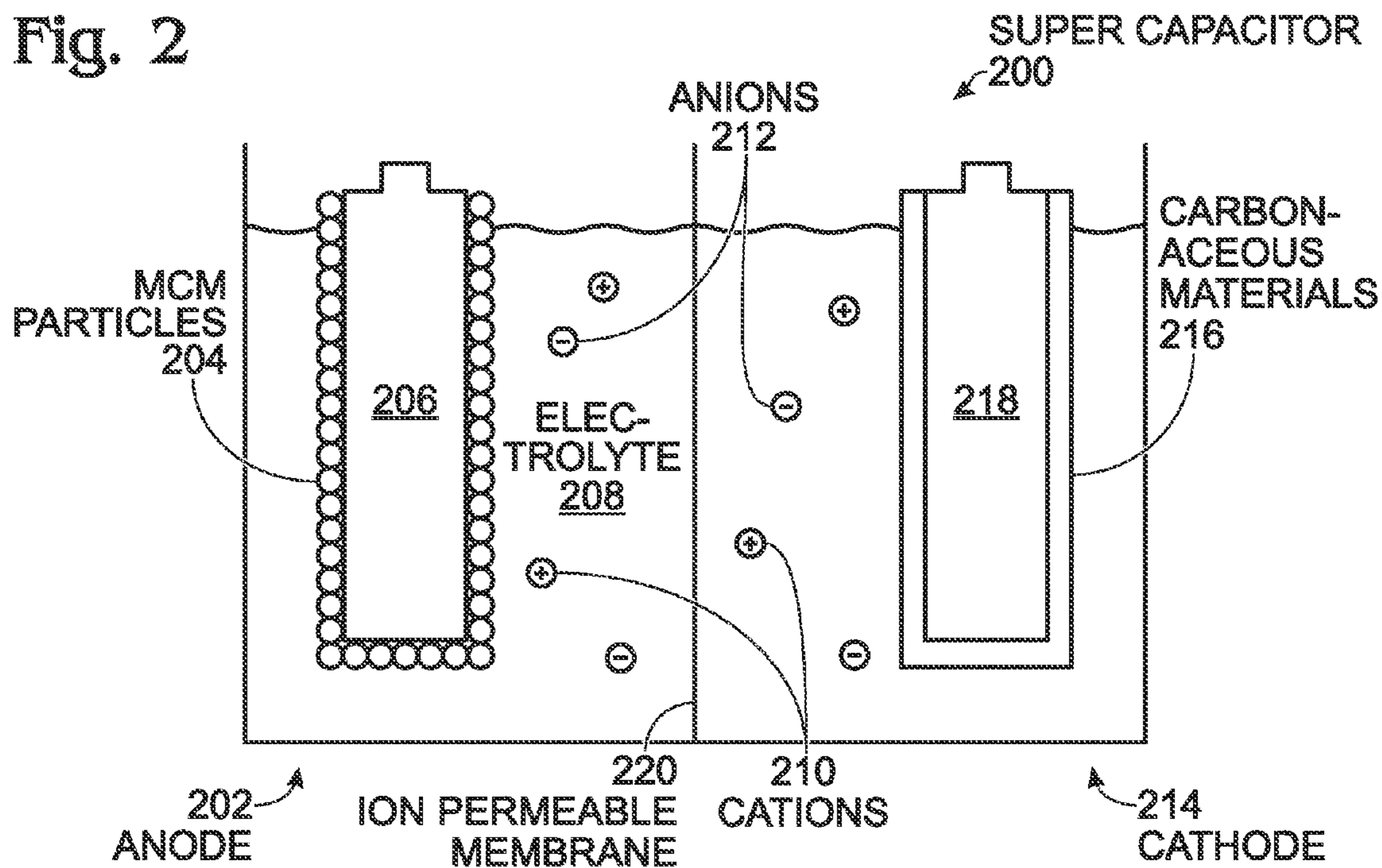


Fig. 3A

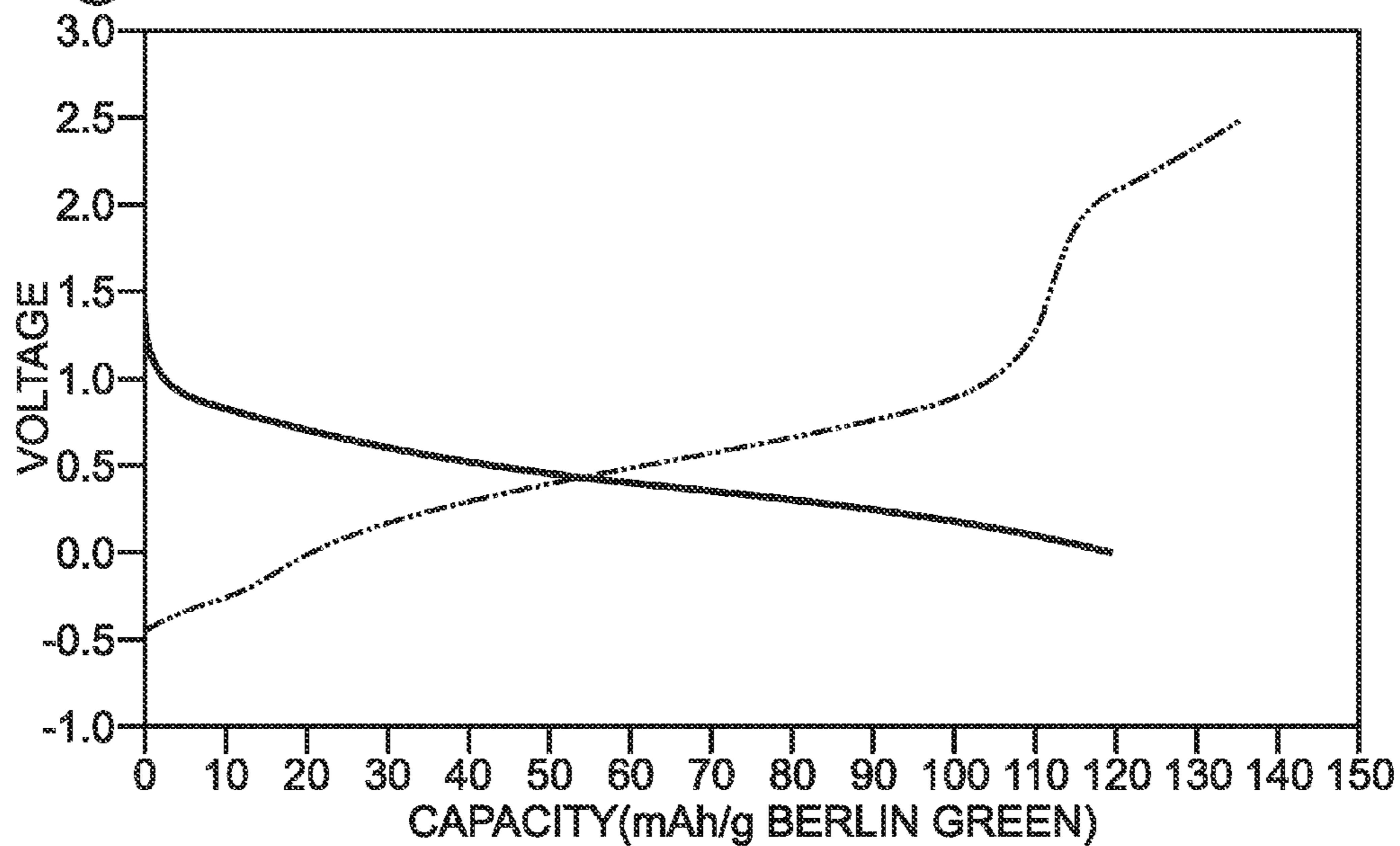
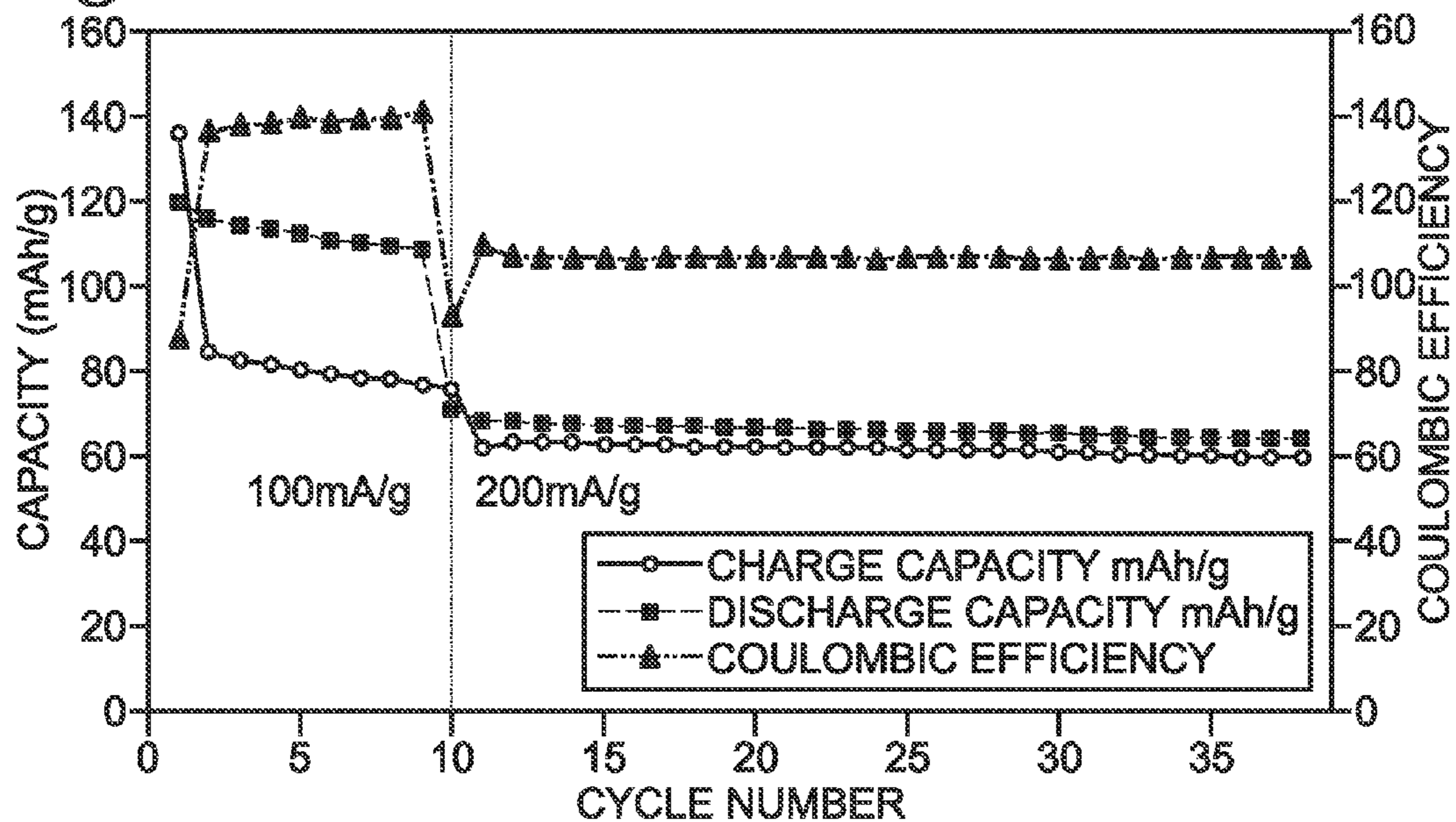
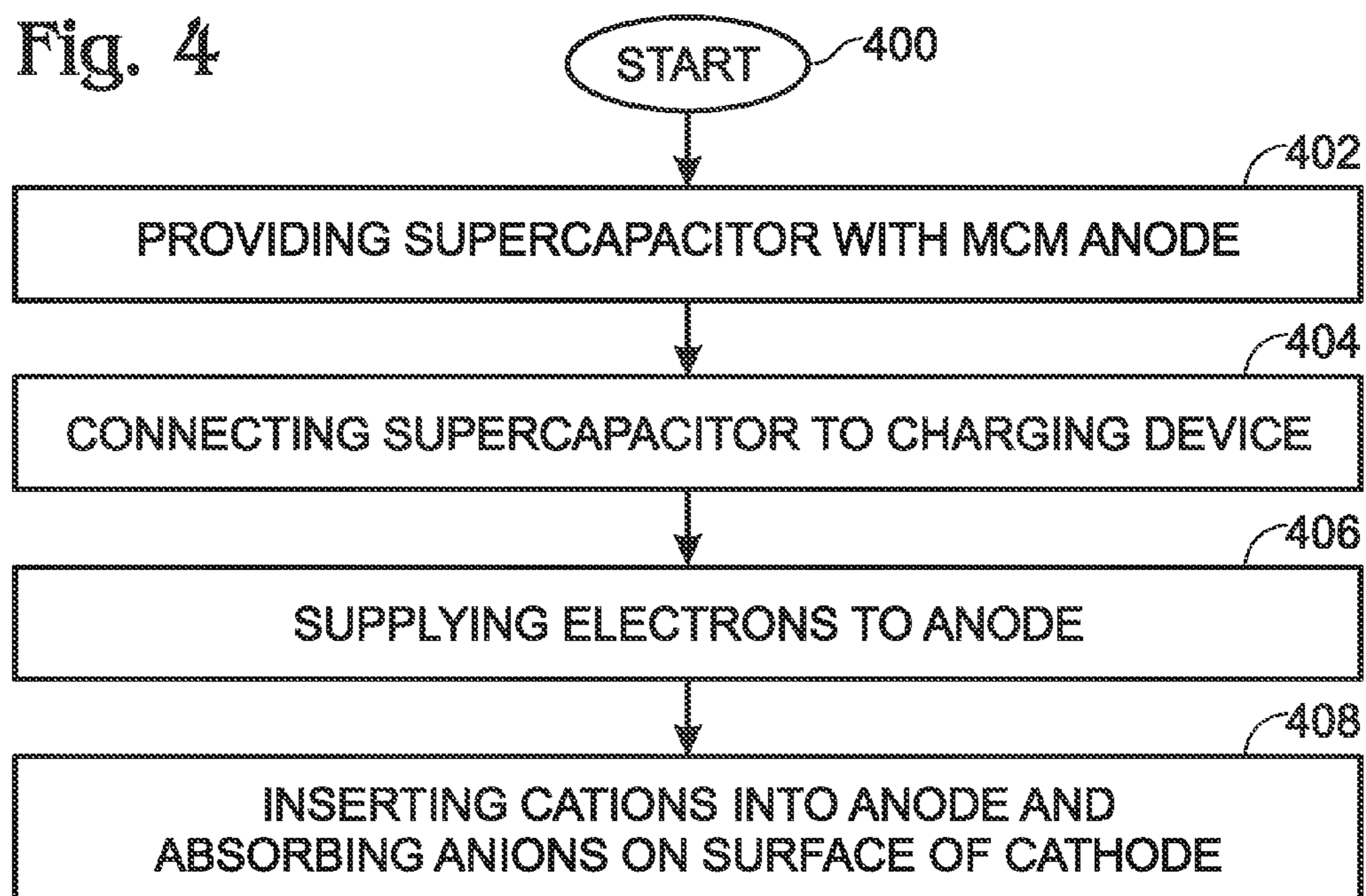


Fig. 3B





**SUPERCAPACITOR WITH METAL  
CYANOMETALLATE ANODE AND  
CARBONACEOUS CATHODE**

RELATED APPLICATIONS

This application is a Continuation-in-Part of an application entitled, SUPERCAPACITOR WITH HEXACYANOMETALLATE CATHODE, ACTIVATED CARBON ANODE, AND AQUEOUS ELECTROLYTE, invented by Yuhao Lu et al., Ser. No. 13/603,322, filed Sep. 4, 2012;

which is a Continuation-in-Part of an application entitled, IMPROVEMENT OF ELECTRON TRANSPORT IN HEXACYANOMETALLATE ELECTRODE FOR ELECTROCHEMICAL APPLICATIONS, invented by Yuhao Lu et al., Ser. No. 13/523,694, filed Jun. 14, 2012;

which is a Continuation-in-Part of an application entitled, ALKALI AND ALKALINE-EARTH ION BATTERIES WITH HEXACYANOMETALLATE CATHODE AND NON-METAL ANODE, invented by Yuhao Lu et al., Ser. No. 13/449,195, filed Apr. 17, 2012;

which is a Continuation-in-Part of an application entitled, ELECTRODE FORMING PROCESS FOR METAL-ION BATTERY WITH HEXACYANOMETALLATE ELECTRODE, invented by Yuhao Lu et al., Ser. No. 13/432,993, filed Mar. 28, 2012. All the above-referenced applications are incorporated herein by reference.

This invention was made with Government support under DE-AR0000297 awarded by DOE. The Government has certain rights in this invention.

BACKGROUND OF THE INVENTION

1. Field of the Invention

This invention generally relates to electrochemical capacitors and, more particularly, to a supercapacitor made from a hexacyanometallate cathode and activated carbon anode.

2. Description of the Related Art

A supercapacitor, or electrochemical capacitor (EC), constitutes one type of device for electrochemical energy storage and conversion. The electrochemical capacitor consists of two electrodes separated by an electrolyte-soaked separator by which the two electrodes are electrically isolated. Based upon the electrode type and the energy storage mechanism, the supercapacitor may be classified into one of the two following categories: (1) an electric double layer capacitor (EDLC), in which the energy is stored at the interface between the electrode and electrolyte through electrostatic charge accumulation, or (2) a pseudo-capacitor (or ultra-capacitor), whereby one electrode undergoes faradic reactions while the other electrode maintains the electrostatic charge accumulation.

In comparison to batteries and fuel cells, supercapacitors have the highest power density (watt per kilogram) due to the rapid movement of ions between the electrode and electrolyte. However, at the same time, the energy storage mechanism restricts its energy density (watt-hours per kilogram). Charge adsorption on the electrode surface dominates the energy storage in EDLCs. The performance of electrode materials can be evaluated by capacitance (F/g, Farad/gram), which can be defined as the charge accumulation with the voltage change per gram of electrode material:  $C=(\Delta Q/\Delta V)/m$ , where Q is the accumulated charge, V is the voltage of the electrode materials, and m is the mass of the active materials of the electrode. The state-of-the-art commercial activated carbon materials have surface areas of

1000-3500 m<sup>2</sup>/g and capacitances of ~200 F/g [1]. Physical adsorption of the electrostatic charge restricts the capacitance from further increases. Therefore, the introduction of faradic reactions to supercapacitors results in the so-called pseudo-/ultra-capacitors.

In general, pseudo-capacitors demonstrate much larger capacitances than EDLC because Faradic reactions can store charges both on the surface and in the bulk of the electrode materials. Ruthenium oxide (RuO<sub>2</sub>), for example, exhibits a high capacitance of 720 F/g [2] based upon the faradic reaction of  $RuO_x(OH)_y + zH^+ + ze^- \leftarrow \rightarrow RuO_{x-2}(OH)_{y+z}$  where the redox couple, Ru<sup>3+/4+</sup>, is reversible during the dis/charge process. Except for the appropriate redox couples, a robust material for the pseudo-capacitor electrode must demonstrate fast transport of charges and electrons in its structure(s), in order to ensure a high power density. Although Faradic reactions increase the capacitance of electrode materials significantly, both the transfer of charges and migration of ions result in a change of volume, which deteriorates their structure during cycling. For that reason, pseudo-/ultra-capacitors exhibit a shorter cycling life than EDLCs. Thus, more stable materials are actively being developing for this class of capacitor.

FIG. 1 depicts the crystal structure of a metal hexacyanometallate (prior art). Prussian blue analogues belong to a class of mixed valence compounds called transition metal hexacyanometallates. The hexacyanometallates have a general formula A<sub>m</sub>M1<sub>x</sub>M2<sub>y</sub>(CN)<sub>6</sub>, where M1 and M2 are transition metals. In many cases, the transition metal hexacyanometallates may contain a variety of ions (A=Li<sup>+</sup>, Cs<sup>+</sup>, Na<sup>+</sup>, K<sup>+</sup>, NH<sub>4</sub><sup>+</sup>, Co<sup>2+</sup>, Cu<sup>2+</sup>, etc.) and various amounts of water in the crystal structure. As is shown in the figure, the crystal structure of metal hexacyanometallates has an open framework which can facilitate fast and reversible intercalation processes for alkali and alkaline ions (A<sub>m</sub>). The number of alkali or alkaline ions in the large cages of this crystallographically porous framework may vary from m=0 to m=2 depending on the valence of M1 and M2.

Twenty years ago, Widmann, et al, demonstrated that K<sup>30</sup>-ions reversibly insert/deinsert into/from the copper, nickel, and iron hexacyanoferrates/hexacyanocobaltates Prussian blue analogues, KNiFe(CN)<sub>6</sub>, KCuFe(CN)<sub>6</sub>, and KFeFe(CN)<sub>6</sub> in aqueous solution [3] Eftekhari [4] assembled an iron hexacyanoferrate (Prussian blue)/potassium battery with an organic electrolyte [1M KBF<sub>4</sub> in ethylene carbonate/ethylmethyl carbonate (3:7 by wt.)]. The results proved that Prussian blue was a good electrode material for the potassium-ion battery with a reversible capacity of ca. 75 mAh/g.

Dr. Goodenough's, group [5] investigated a series of Prussian blue analogues in a sodium battery with organic electrolyte, and found that KFe(II)Fe(III)(CN)<sub>6</sub> demonstrated the highest capacity of ca. 95 mAh/g, while KMnFe(CN)<sub>6</sub>, KNiFe(CN)<sub>6</sub>, KCuFe(CN)<sub>6</sub>, and KCoFe(CN)<sub>6</sub> demonstrated a capacity of 50~70 mAh/g. In the first 30 cycles, the capacity retention of KFeFe(CN)<sub>6</sub> was higher than 97%.

Recently, Cui's group studied the Na<sup>+</sup>/K<sup>+</sup> ion intercalation of copper (KCuFe(CN)<sub>6</sub>) and nickel hexacyanoferrates (KNiFe(CN)<sub>6</sub>) in aqueous solution. Their results demonstrated the rapid movement of Li<sup>+</sup>, Na<sup>+</sup>, K<sup>+</sup>, and NH<sub>4</sub><sup>+</sup>-ions in the Prussian blue analogues, as well as long cycling life for the electrode materials [6-8]. Patent application Ser. No. 13/603,322, Supercapacitor with Hexacyanometallate Cathode, Activated Carbon Anode, and Aqueous Electrolyte, incorporated herein by reference, describes a method for fabricating a supercapacitor with a hexacyanometallate (positive electrode), an activate carbon (negative electrode),

and an aqueous electrolyte containing metal salt. Alkali ion or alkaline earth ions are inserted in, and extracted from the hexacyanometallate lattice during the charge/discharge of the supercapacitor. In this kind of supercapacitor, cations have to be released from the hexacyanometallates first, and then they are absorbed on the surface of activated carbon. The process corresponds to a charge process where the potential for hexacyanometallates becomes more positive and for activated carbon is more negative. The fast ion movement in MHCs makes it possible for this material to perform effectively as the electrode in supercapacitors.

It would be advantageous if during charge, cations in electrolyte could be inserted into the metal cyanometallate electrode to make its potential more negative, while anions are absorbed onto the surface of activated carbon to make its potential more positive.

It would be advantageous if both cations and anions could move back and forth between positive and negative electrodes during the charge and discharge cycles.

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### SUMMARY OF THE INVENTION

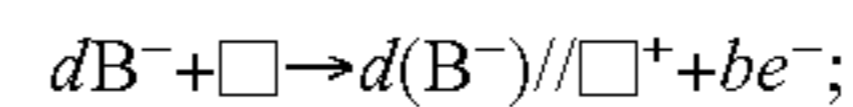
Unlike the reported work cited above in the Background Section, a supercapacitor is described herein that has a metal cyanometallate (MCM) electrode that functions as the negative electrode (anode), and carbonaceous materials that perform as positive electrode (cathode). During charge, cations in electrolyte are inserted into the MCMs electrode to make its potential more negative, and anions are absorbed onto the surface of activated carbon to make its potential becomes more positive. Further, both cations and anions move back and forth between positive and negative electrodes during the charge and discharge cycle.

More explicitly, the MCM material can be described using the chemical formula of  $A_xM_1yM_2z(CN)_N \cdot nH_2O$ . M1 and M2 may be the same or different metal ions, such as titanium (Ti), vanadium (V), chromium (Cr), manganese (Mn), iron (Fe), cobalt (Co), nickel (Ni), copper (Cu), zinc (Zn), Ca, Mg, strontium (Sr), and barium (Ba). "A" may be selected

from a broad group of cations including alkali and alkaline earth metals. The electrolyte may be an aqueous, non-aqueous, polymer, gel, or solid electrolyte. The electrolyte contains salts, DB, to realize the energy storage and conversion. The cations, D, can be hydrogen ( $H^+$ ), lithium ( $Li^+$ ), sodium ( $Na^+$ ), potassium ( $K^+$ ), ammonium ( $NH_4^+$ ), rubidium ( $Rb^+$ ), cesium ( $Cs^+$ ), magnesium ( $Mg^{2+}$ ), calcium ( $Ca^{2+}$ ), strontium ( $Sr^{2+}$ ), barium ( $Ba^{2+}$ ), cobalt ( $Co^{2+}$ ), iron ( $Fe^{2+}$ ),  $Fe^{3+}$ , copper ( $Cu^{2+}$ ), tetramethylammonium, tetraethylammonium, or complex cations. The anions, B, can be selected from fluorine (F), chlorine (Cl), bromine (Br), iodine (I), carbon trioxide ( $CO_3$ ), sulfur trioxide ( $SO_3$ ), sulfate ( $SO_4$ ), phosphate ( $PO_4$ ), aluminate anion ( $AlO_2$ ), nitrate ( $NO_3$ ), hydroxide ( $OH^-$ ), perchlorate ( $ClO_4$ ), tetrafluoroborate anion ( $BF_4^-$ ), hexafluorophosphate ( $PF_6$ ), hexafluoroarsenate ion ( $AsS_6$ ), trifluoromethanesulfonic ( $CF_3SO_3$ ), N-fluoromethanesulfony ( $N(SO_2CF_3)_2$ ), N-fluoroethanesulfony imide ( $N(SO_2CF_2CF_3)_2$ ), complex anions, or combinations thereof. The supercapacitor demonstrates a high power density due to the rapid ion-transport, and a high capacitance due to the ion interaction in the MCM electrode.

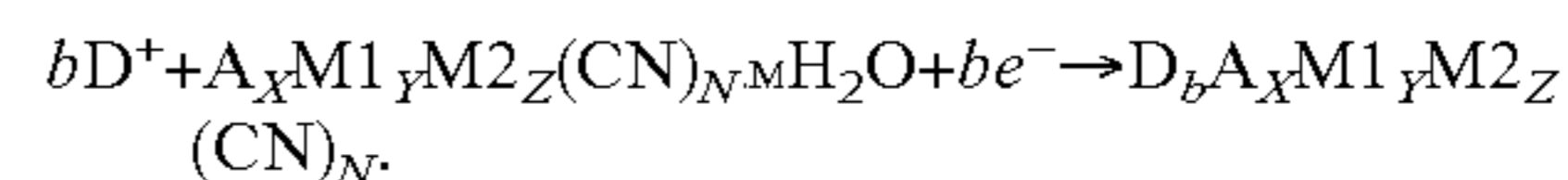
Accordingly, a method is provided for charging a supercapacitor. The method initially provides a supercapacitor with a MCM particle anode, an electrolyte including a salt (DB) made up of cations ( $D^+$ ) and anions ( $B^-$ ), and a cathode including carbonaceous materials ( $\square$ ). The method connects an external charging device between the anode and cathode, and the charging device supplies electrons to the anode and accepts electrons from the cathode. In response to the charging device, cations are inserted into the anode while anions are absorbed on the surface of the cathode.

More explicitly, anions are absorbed at the cathode as follows:



where "d" and "b" are quantities.

At the same time, cations are inserted into the anode as follows:



Additional details of the above-described method and a supercapacitor device are presented below.

### BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1 depicts the crystal structure of a metal hexacyanometallate (prior art).

FIG. 2 is a partial cross-sectional view of a supercapacitor.

FIGS. 3A and 3B demonstrate the behavior of a supercapacitor with an activated carbon positive electrode and a Berlin Green negative electrode.

FIG. 4 is a flowchart illustrating a method for charging a supercapacitor.

### DETAILED DESCRIPTION

FIG. 2 is a partial cross-sectional view of a supercapacitor. The supercapacitor 200 comprises an anode 202 including metal cyanometallate, (MCM) particles 204 overlying a current collector 206. The MCM particles 204 have the chemical formula  $A_xM_1yM_2z(CN)_N \cdot nH_2O$ ;

where "A" is selected from a first group of metals;

where M1 and M2 are transition metals;

where X is less than or equal to 2;

where Y is less than or equal to 1;

## 5

where Z is less than or equal to 1;  
where N is less than or equal to 6; and,  
where M is less than or equal to 20.

An electrolyte **208** includes cations **210** selected from a second group of materials and anions **212** selected from a third group of materials. A cathode **214** including carbonaceous materials **216** overlies a current collector **218**.

The first group of metals includes alkali metals, alkaline earth metals, and combinations thereof. More explicitly, the first group of metals includes lithium (Li), sodium (Na), potassium (K), rubidium (Rb), cesium (Cs), calcium (Ca), strontium (Sr), barium (Ba), silver (Ag), aluminum (Al), and magnesium (Mg). M1 is a metal with 2<sup>+</sup> or 3<sup>+</sup> valance positions. Likewise, M2 is a metal with 2<sup>+</sup> or 3<sup>+</sup> valance positions. M1 and M2 are each independently derived, meaning they may be the same metal or different metals. Some examples of typical M1 and M2 metals include titanium (Ti), vanadium (V), chromium (Cr), manganese (Mn), iron (Fe), cobalt (Co), nickel (Ni), copper (Cu), zinc (Zn), Ca, Mg, strontium (Sr), and barium (Ba).

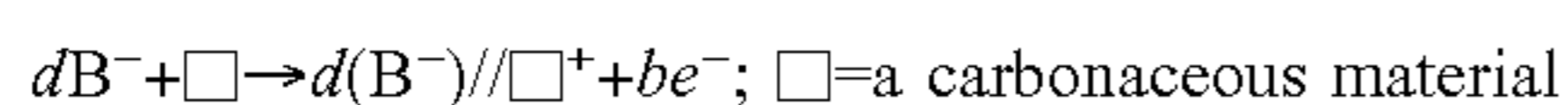
The second group of materials that make up the cations **210** include hydrogen (H), Li, Na, K, ammonium (NH<sub>4</sub>), Rb, Cs, Mg, Ca, Sr, Ba, Co, Fe, Cu, tetramethylammonium, tetraethylammonium, and combinations thereof. The third group of materials that make up the anions **212** include fluorine (F), chlorine (Cl), bromine (Br), iodine (I), carbon trioxide (CO<sub>3</sub>), sulfur trioxide (SO<sub>3</sub>), sulfate (SO<sub>4</sub>), phosphate (PO<sub>4</sub>), aluminate anion (AlO<sub>2</sub>), nitrate (NO<sub>3</sub>), hydroxide (OH<sup>-</sup>), perchlorate (ClO<sub>4</sub>), tetrafluoroborate anion (BF<sub>4</sub><sup>-</sup>), hexafluorophosphate (PF<sub>6</sub>), hexafluoroarsenate ion (AsS<sub>6</sub>), trifluoromethanesulfony (CF<sub>3</sub>SO<sub>3</sub>), N-fluoromethanesulfony (N(SO<sub>2</sub>CF<sub>3</sub>)<sub>2</sub>), N-fluoroethanesulfony imide (N(SO<sub>2</sub>CF<sub>2</sub>CF<sub>3</sub>)<sub>2</sub>), and combinations thereof.

The electrolyte **208** may be an aqueous, non-aqueous, polymer, gel, or solid electrolyte. Typically, an ion permeable membrane **220** is used to separate the anode **202** from the cathode **214**. Both the MCM particles **204** and carbonaceous materials **216** are porous materials that enable electrolyte to fill their pores. The carbonaceous materials **216** of the cathode **214** may be activated carbon, carbon black, carbon paper, or carbon cloth.

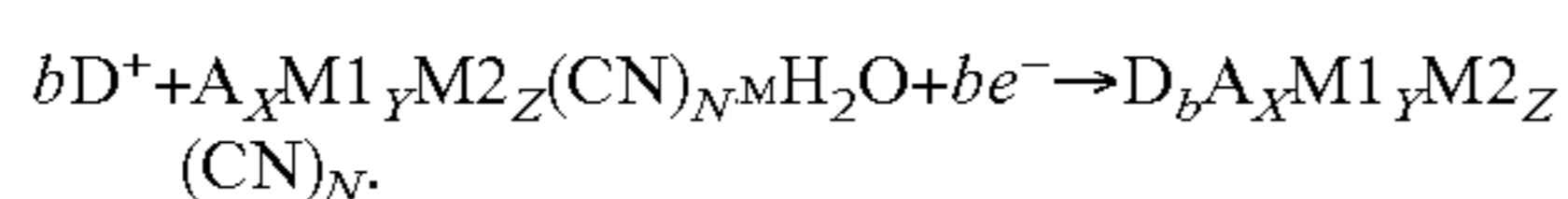
The MCM particles A<sub>x</sub>M<sub>1</sub><sub>y</sub>M<sub>2</sub><sub>z</sub>(CN)<sub>N</sub>MH<sub>2</sub>O demonstrate frameworks that consist of M1-N—C-M2 skeletons and large interstitial space as shown in FIG. 1 that “A” cations can occupy. The cations can be quickly and reversibly inserted/extracted into/out their interstitial spaces, making MCM a good electrode material for supercapacitors. Carbonaceous materials (e.g. activated carbon) are used as the counter electrode. To realize the ion transport between the two electrodes, aqueous, non-aqueous, gel, polymer, or solid electrolytes can be used between them.

To explain the mechanism of the supercapacitor, it is assumed that a salt, DB, is dissolved in the electrolyte. During charge, cations, D<sup>+</sup>, are inserted into MCM electrode (anode or negative electrode), and anions, B<sup>-</sup>, are absorbed onto the surface of carbonaceous electrode (cathode or positive electrode). Meanwhile, electrons move from positive electrode to negative electrode through an external circuit (current source or charger). The process can be described as:

Positive electrode:



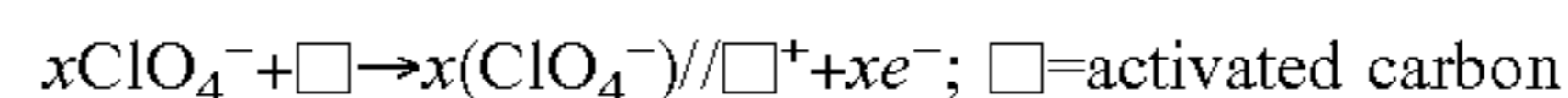
Negative electrode:



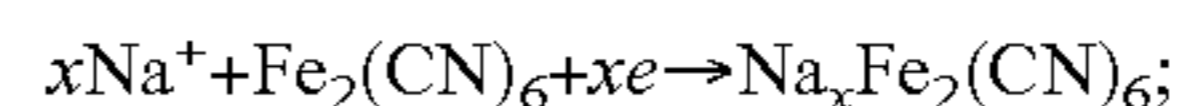
## 6

As an example, a supercapacitor with Berlin Green (A<sub>x</sub>Fe<sub>2</sub>(CN)<sub>6</sub>·yH<sub>2</sub>O, x=0) anode and activated hard carbon cathode was assembled with an electrolyte of NaClO<sub>4</sub> in propylene carbonate (PC). In this kind of supercapacitor, the following electrochemical reactions occur during the charging process.

Positive electrode:



Negative electrode:



The reaction on the positive electrolyte occurs quickly because the anions are just absorbed on the electrode surface. As to the anodic reaction, sodium-ions have to diffuse into the interstitial space of Berlin Green material. This step has been evaluated in an electrochemical cell consisting of Berlin Green electrode and sodium metal electrode. Berlin Green showed an excellent rate capability.

FIGS. 3A and 3B demonstrate the behavior of a supercapacitor with an activated carbon positive electrode and a Berlin Green negative electrode. At a current of 100 milliamps per gram (mA/g), the Berlin Green supercapacitor delivered a capacity of ~110 milliamp hours per gram (mAh/g). After optimizing the electrode ratio and electrolyte, the supercapacitor worked at a high power density with a considerable energy density. FIG. 3A depicts the voltage vs. capacity of the Berlin Green supercapacitor in the first charge/discharge cycle. FIG. 3B depicts the capacity retention of the Berlin Green supercapacitor.

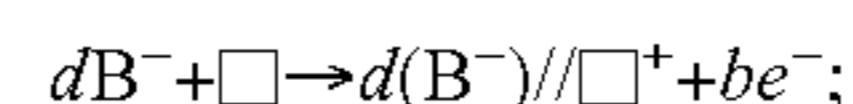
FIG. 4 is a flowchart illustrating a method for charging a supercapacitor. Although the method is depicted as a sequence of numbered steps for clarity, the numbering does not necessarily dictate the order of the steps. It should be understood that some of these steps may be skipped, performed in parallel, or performed without the requirement of maintaining a strict order of sequence. Generally however, the method follows the numeric order of the depicted steps. The method starts at Step 400.

Step 402 provides supercapacitor comprising a metal cyanometallate (MCM) particle anode, an electrolyte including a salt (DB) comprising cations (D<sup>+</sup>) and anions (B<sup>-</sup>), and a cathode including carbonaceous materials (□), see FIG. 2. Step 404 connects an external charging device (current source) between the anode and cathode. In Step 406 the charging device supplies electrons to the anode and accepts electrons from the cathode. In response to the charging device, Step 408 inserts cations into the anode, and absorbs anions on a surface of the cathode.

Providing the anode in Step 402 includes the MCM particles having the chemical formula. A<sub>x</sub>M<sub>1</sub><sub>y</sub>M<sub>2</sub><sub>z</sub>(CN)<sub>N</sub>MH<sub>2</sub>O;

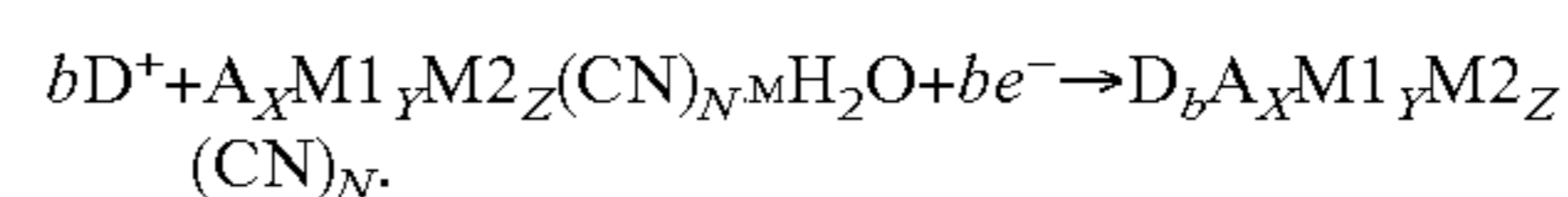
where “A” is selected from a first group of metals;  
where M1 and M2 are transition metals;  
where X is less than or equal to 2;  
where Y less than or equal to 1;  
where Z is less than or equal to 1;  
where N is less than or equal to 6; and,  
where M is less than or equal to 20.

Step 408 performs the following reaction at the cathode:



where “d” and “b” are quantities;

Step 406 performs the following reaction at the anode:





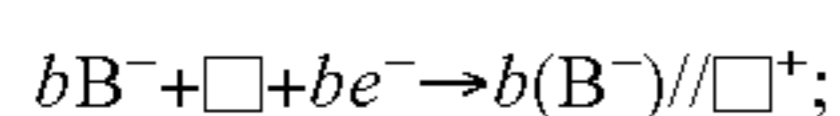
As noted above in the description of FIG. 2, the first group of metals includes alkali metals, alkaline earth metals, and combinations thereof. Specific examples from the first group of metals include lithium (Li), sodium (Na), potassium (K), rubidium (Rb), cesium (Cs), calcium (Ca), strontium (Sr), barium (Ba), silver (Ag), aluminum (Al), and magnesium (Mg).

M1 and M2 are each independently derived, and are typically selected from the following group: titanium (Ti), vanadium (V), chromium (Cr), manganese (Mn), iron (Fe), cobalt (Co), nickel (Ni), copper (Cu), zinc (Zn), Ca, Mg, strontium (Sr), and barium (Ba). The cations may be hydrogen (H), Li, Na, K, ammonium (NH<sub>4</sub>), Rb, Cs, Mg, Ca, Sr, Ba, Co, Fe, Cu, tetramethylammonium, tetraethylammonium, or combinations thereof. The anions may be fluorine (F), chlorine (Cl), bromine (Br), iodine (I), carbon trioxide (CO<sub>3</sub>), sulfur trioxide (SO<sub>3</sub>), sulfate (SO<sub>4</sub>), phosphate (PO<sub>4</sub>), aluminate anion (AlO<sub>2</sub>), nitrate (NO<sub>3</sub>), hydroxide (OH<sup>-</sup>), perchlorate (ClO<sub>4</sub>), tetrafluoroborate anion (BF<sub>4</sub><sup>-</sup>), hexafluorophosphate (PF<sub>6</sub>), hexafluoroarsenate ion (AsS<sub>6</sub>), trifluoromethanesulfonic (CF<sub>3</sub>SO<sub>3</sub>), N-fluoromethanesulfony (N(SO<sub>2</sub>CF<sub>3</sub>)<sub>2</sub>), N-fluoroethanesulfony imide (N(SO<sub>2</sub>CF<sub>2</sub>CF<sub>3</sub>)<sub>2</sub>), or combinations thereof.

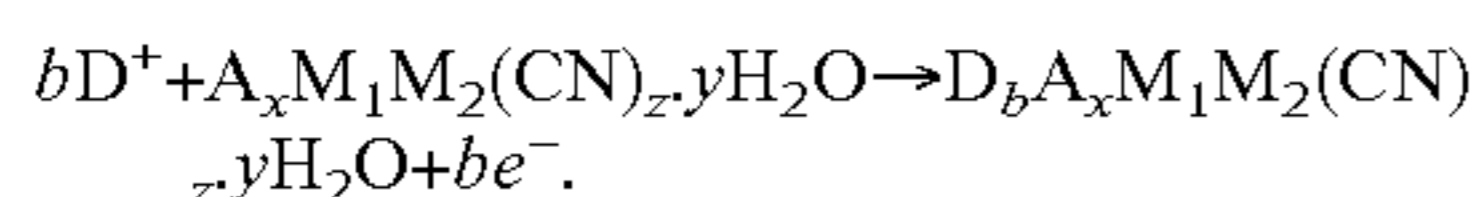
The electrolyte may be an aqueous, non-aqueous, polymer, gel, or solid electrolytes. The carbonaceous materials of the cathode may be activated carbon, carbon black, carbon paper, or carbon cloth.

Although not explicitly shown in FIG. 4, the process of discharging the supercapacitor is essentially the reverse of the charging process, with the anode and cathode being connected to a load instead of a current source. The reactions at the anode and cathode during discharge are presented below.

Positive electrode:



Negative electrode:



A supercapacitor with a metal cyanometallate anode and carbon cathode has been provided with an associated charging method. Examples of particular materials and process steps have been presented to illustrate the invention. However, the invention is not limited to merely these examples. Other variations and embodiments of the invention will occur to those skilled in the art.

We claim:

1. A supercapacitor comprising:

an anode comprising metal cyanometallate (MCM) particles overlying a current collector, the MCM particles having a chemical formula A<sub>x</sub>M<sub>1</sub><sub>y</sub>M<sub>2</sub><sub>z</sub>(CN)<sub>N</sub>·mH<sub>2</sub>O; where "A" is selected from a first group of metals; where M1 and M2 are transition metals; where X is less than or equal to 2; where Y is less than or equal to 1; where Z is less than or equal to 1; where N is less than or equal to 6; where m is less than or equal to 20;

a cathode including carbonaceous cathode materials overlying a current collector; and,

an electrolyte including cations capable of insertion/de-insertion with the anode and selected from a second group of materials, and anions capable of adsorption/de-adsorption on a surface of the cathode and selected from a third group of materials.

2. The supercapacitor of claim 1 wherein the first group of metals is selected from a group consisting of alkali metals, alkaline earth metals, and combinations thereof.

3. The supercapacitor of claim 2 wherein the first group of metals is selected from a group of metals consisting of lithium (Li), sodium (Na), potassium (K), rubidium (Rb), cesium (Cs), calcium (Ca), strontium (Sr), barium (Ba), silver (Ag), aluminum (Al), and magnesium (Mg).

4. The supercapacitor of claim 1 wherein M1 and M2 are each independently derived, as selected from a group consisting of titanium (Ti), vanadium (V), chromium (Cr), manganese (Mn), iron (Fe), cobalt (Co), nickel (Ni), copper (Cu), zinc (Zn).

5. The supercapacitor of claim 1 wherein the second group of materials is selected from a group consisting of hydrogen (H), Li, Na, K, ammonium (NH<sub>4</sub>), Rb, Cs, Mg, Ca, Sr, Ba, Co, Cu, tetra ethylammonium, tetraethylammonium, and combinations thereof.

6. The supercapacitor of claim 1 wherein the third group of materials is selected from a group consisting of fluorine (F), chlorine (Cl), bromine (Br), iodine (I), carbon trioxide (CO<sub>3</sub>), sulfur trioxide (SO<sub>3</sub>), sulfate (SO<sub>4</sub>), phosphate (PO<sub>4</sub>), aluminate anion (AlO<sub>2</sub>), nitrate (NO<sub>3</sub>), hydroxide (OH<sup>-</sup>), perchlorate (ClO<sub>4</sub>), tetrafluoroborate anion (BF<sub>4</sub><sup>-</sup>), hexafluorophosphate (PF<sub>6</sub>), hexafluoroarsenate ion (AsS<sub>6</sub>), trifluoromethanesulfonic (CF<sub>3</sub>SO<sub>3</sub>), N-fluoromethanesulfony (N(SO<sub>2</sub>CF<sub>3</sub>)<sub>2</sub>), N-fluoroethanesulfony imide (N(SO<sub>2</sub>CF<sub>2</sub>CF<sub>3</sub>)<sub>2</sub>), and combinations thereof.

7. The supercapacitor of claim 1 wherein the electrolyte is selected from a group consisting of aqueous, non-aqueous, polymer, gel, and solid electrolytes.

8. The supercapacitor of claim 1 wherein the cathode includes carbonaceous cathode materials, selected from a group consisting of activated carbon, carbon black, carbon paper, and carbon cloth, adsorbing/de-adsorbing the anions.

9. A method for charging a supercapacitor, the method comprising:

providing supercapacitor comprising:

a metal cyanometallate (MCM) particle anode, having a chemical formula A<sub>x</sub>M<sub>1</sub><sub>y</sub>M<sub>2</sub><sub>z</sub>(CN)<sub>N</sub>·mH<sub>2</sub>O; where A is selected from a first group of metals; where M1 and M2 are transition metals; where X is less than or equal to 2; where Y is less than or equal to 1; where Z is less than or equal to 1; where N is less than or equal to 6; where m is less than or equal to 20

an electrolyte including a salt (DB) comprising cations (D<sup>+</sup>) from a second group of materials capable of insertion with the anode, and anions (B<sup>-</sup>) from a third group of materials capable of adsorption on a surface of a cathode;

the cathode including carbonaceous materials (□);

connecting an external charging device between the anode and cathode;

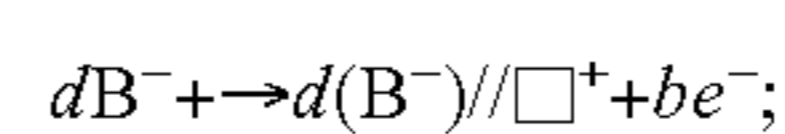
the charging device supplying electrons to the anode and accepting electrons from the cathode;

in response to the charging device:

inserting cations (D<sup>+</sup>) into the anode; and,

adsorbing anions (B<sup>-</sup>) on a surface of the cathode.

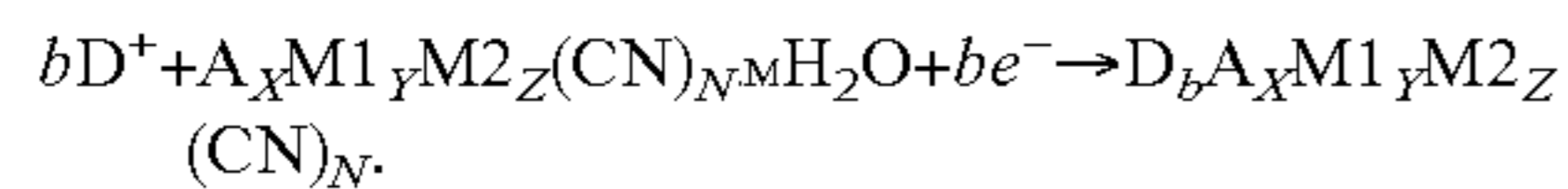
10. The method of claim 9 wherein adsorbing anions on the surface of the cathode during charge includes performing the following reaction at the cathode:



where "d" and "b" are quantities; and,

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wherein inserting cations into the anode includes performing the following reaction at the anode:



**11.** The method of claim **9** wherein where the first group of metals is selected from a group consisting of alkali metals, alkaline earth metals, and combinations thereof.

**12.** The method of claim **11** wherein the first group of metals is selected from a group of metals consisting of lithium (Li), sodium (Na), potassium (K), rubidium (Rb), cesium (Cs), calcium (Ca), strontium (Sr), barium (Ba), silver (Ag), aluminum (Al), and magnesium (Mg).

**13.** The method of claim **9** wherein M1 and M2 are each independently derived, as selected from a group consisting of titanium (Ti), vanadium (V), chromium (Cr), manganese (Mn), iron (Fe), cobalt (Co), nickel (Ni), copper (Cu), zinc (Zn).

**14.** The method of claim **9** wherein cations are a material selected from a group consisting of hydrogen (H), Li, Na, K,

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ammonium (NH<sub>4</sub>), Rb, Cs, Mg, Ca, Sr, Ba, Co, Fe, Cu, tetramethylammonium, tetraethylammonium, and combinations thereof.

**15.** The method of claim **9** wherein the anions are a material selected from a group consisting of fluorine (F), chlorine (Cl), bromine (Br), iodine (I), carbon trioxide (CO<sub>3</sub>), sulfur trioxide (SO<sub>3</sub>), sulfate (SO<sub>4</sub>), phosphate (PO<sub>4</sub>), aluminate anion (AlO<sub>2</sub>), nitrate (NO<sub>3</sub>), hydroxide (OH<sup>-</sup>), perchlorate (PO<sub>4</sub>), tetrafluoroborate anion (BF<sub>4</sub><sup>-</sup>), hexafluorophosphate (PF<sub>6</sub>), hexafluoroarsenate ion (AsS<sub>6</sub>), trifluoromethanesulfonic (CF<sub>3</sub>SO<sub>3</sub>), N-fluoromethanesulfony (N(SO<sub>2</sub>CF<sub>3</sub>)<sub>2</sub>), N-fluoroethanesulfony imide (N(SO<sub>2</sub>CF<sub>2</sub>CF<sub>3</sub>)<sub>2</sub>), and combinations thereof.

**16.** The method of claim **9** wherein the electrolyte is selected from a group consisting of aqueous, non-aqueous, polymer, gel, and solid electrolytes.

**17.** The method of claim **9** wherein the cathode includes carbonaceous cathode materials selected, from a group consisting of activated carbon, carbon black, carbon paper, and carbon cloth, adsorbing the anions.

\* \* \* \* \*

UNITED STATES PATENT AND TRADEMARK OFFICE  
**CERTIFICATE OF CORRECTION**

PATENT NO. : 9,443,664 B2  
APPLICATION NO. : 14/274686  
DATED : September 13, 2016  
INVENTOR(S) : Yuhao Lu, Long Wang and Jong-Jan Lee

Page 1 of 1

It is certified that error appears in the above-identified patent and that said Letters Patent is hereby corrected as shown below:

In the claims,

In column 8, line 17, claim 5, the word "tetramethylammonium" has been incorrectly printed as --tetraethylammonium--. Claim 5 should read as follows:

5. The supercapacitor of claim 1 wherein the second group of materials is selected from a group consisting of hydrogen (H), Li, Na, K, ammonium (NH<sub>4</sub>), Rb, Cs, Mg, Ca, Sr, Ba, Co, Fe, Cu, tetramethylammonium, tetraethylammonium, and combinations thereof.

Signed and Sealed this  
Eighteenth Day of October, 2016



Michelle K. Lee  
*Director of the United States Patent and Trademark Office*